Recent magnetized laboratory astrophysics experiments: studies of jet collimation and collisionless high-velocity shocks

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Outline

- ❖Why magnetized laboratory astrophysics experiments and how?
- ❖Jet collimation study
- ❖Collisionless, high-velocity shocks study
- ❖Perspectives

Background:
« laboratory astrophysics »

- ❖Overall rationale: exploit laboratory **plasma** experiments to access & model phenomena observed in nature

- ❖Temporal and spatial scales are enormously different → exploit scalability and similarity (typology of hydrodynamic flows)

- ❖Various plasmas are exploited: produced by discharge, Z-pinch, **high-power lasers**, etc

- ❖Many fields/phenomena have been/are being studied: planetology (Equation of State), **shocks**, accretions, **jets**, etc… but **most in unmagnetized situations**

Remington, Drake, Takabe et al., Phys. Plasmas 7, 1641 (2000)

How to produce the necessary high B-field and couple it to a high-power laser platform?

- By short-pulse laser / VULCAN (U.K.) or long-pulse / Osaka (Japan) → short duration

  [C.Courtois et al., JAP 98 054913 (2005)
  S. Fujioka et al., Sci. Rep 3, 1170 (2013)]

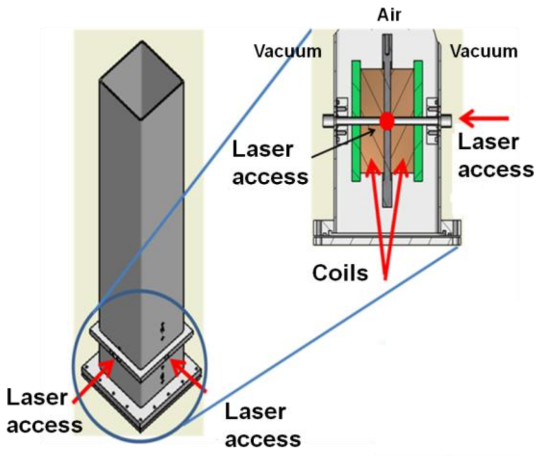
- With coils in vacuum / LLNL (USA) → possible heating issue, limitation in amplitude

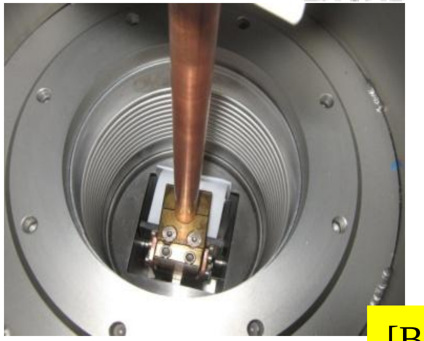
  [B.B Pollock et al., Rev. Sci. Instru. 77 114703 (2006)]

- With windings in vacuum / Omega (USA) → material in chamber, single use

  [O.V. Gotchev et al., Phys. Rev. Lett, 103, 215004 (2009)]

Our approach:

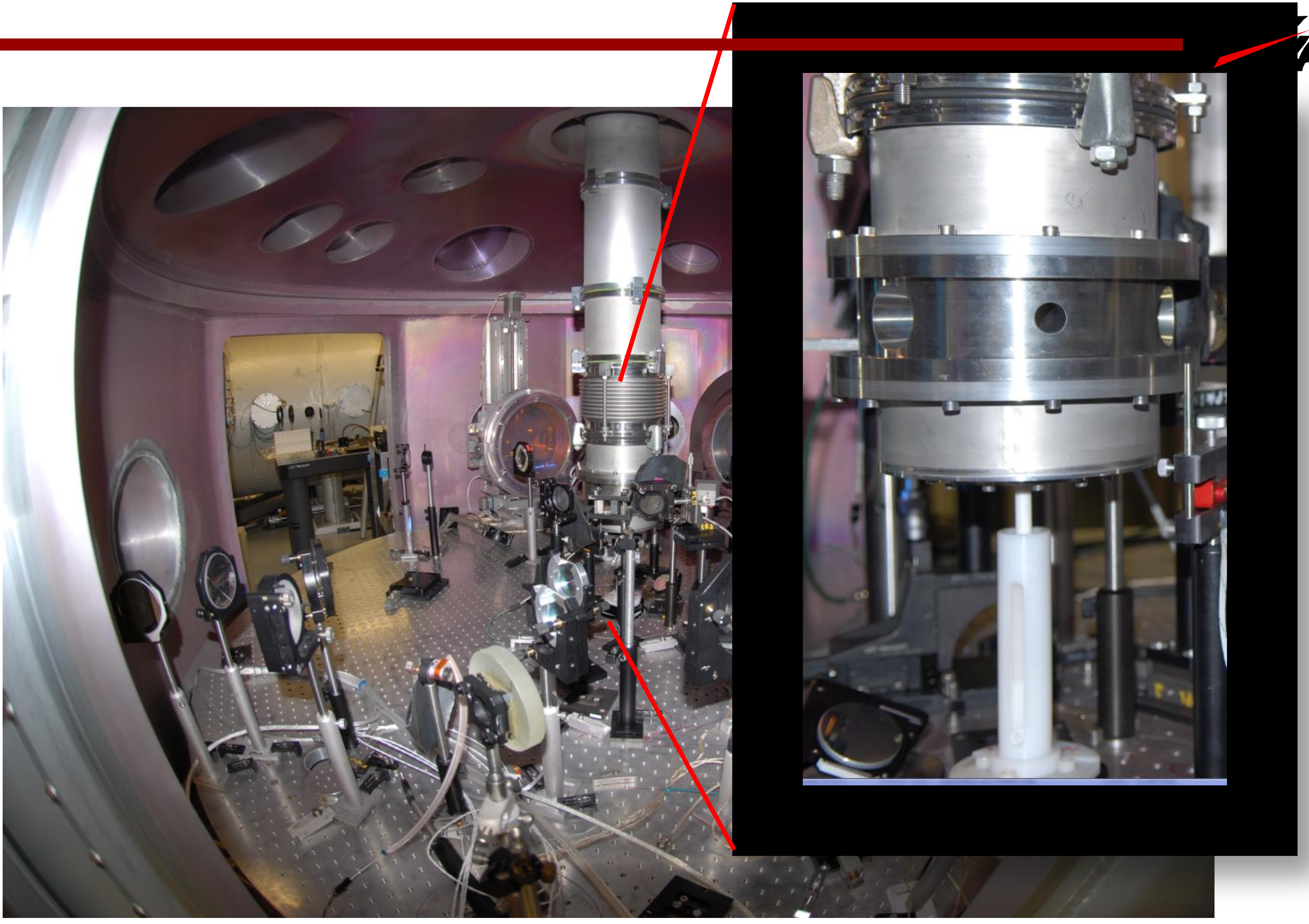




- Coil contained: NO DEBRIS
- Reduced thermal load
- Drastic diminution of risks of arcing between experimental chamber and transmission line

[B. Albertazzi et al., Rev. Sci. Instru 84, 043505 (2013)]

In JLF-Titan: Chamber View



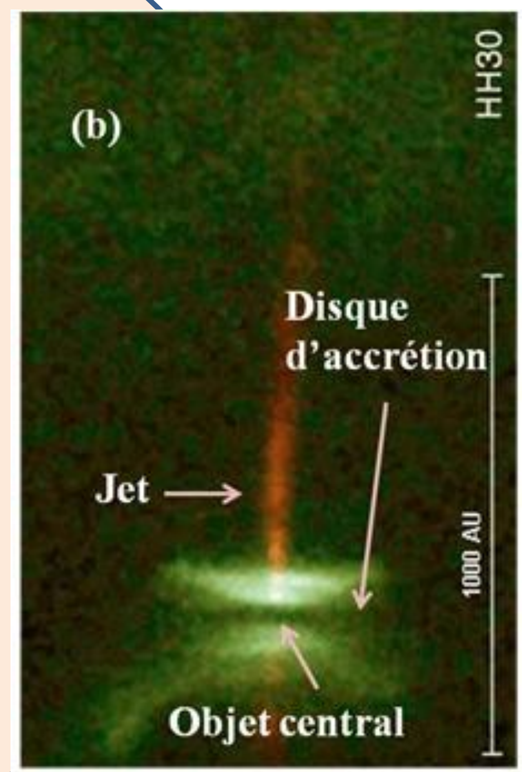
First focus: jets
Where are astrophysical jets coming from?

Wikipedia:

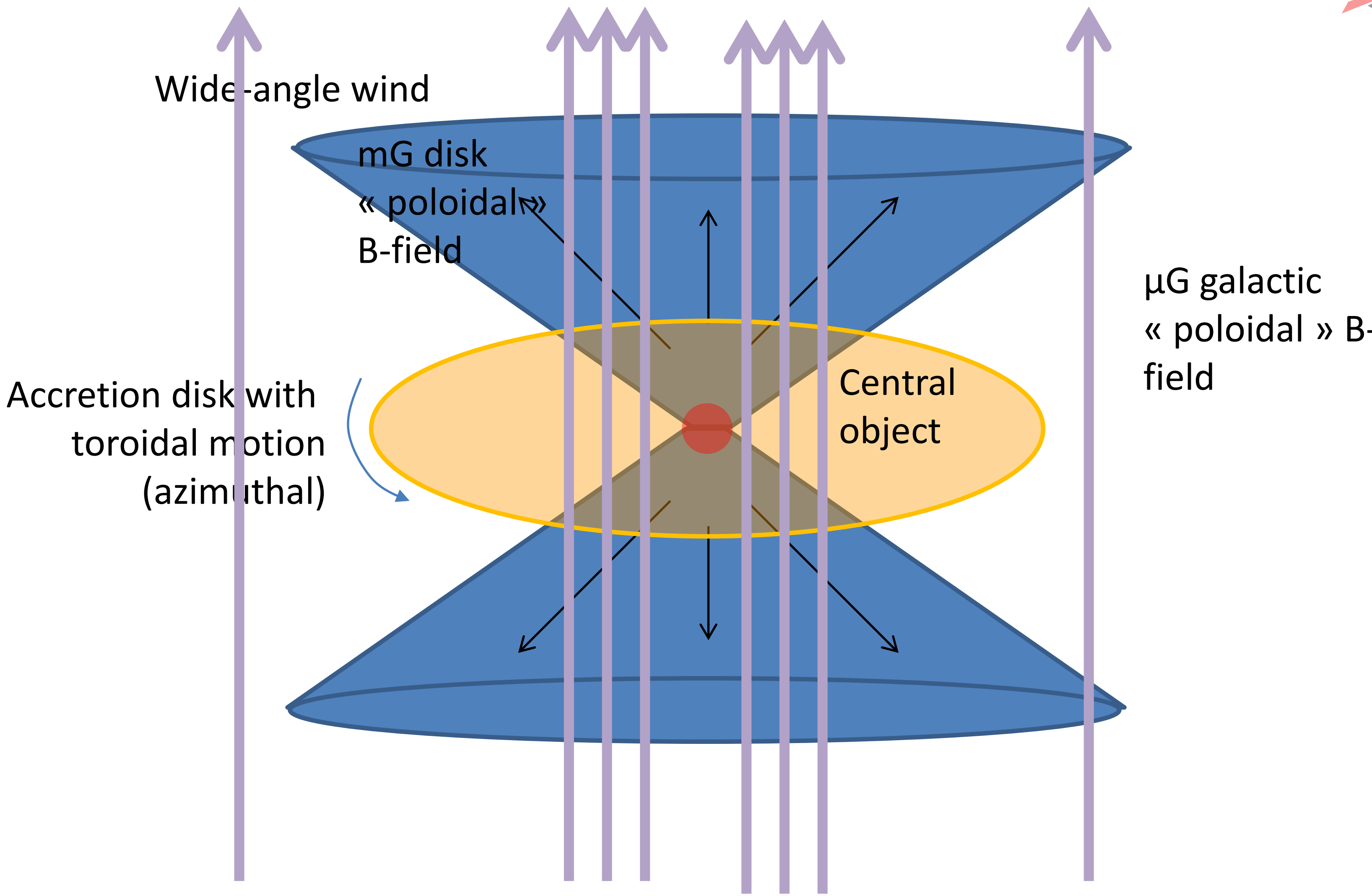
List of unsolved problems in physics

Accretion disc jets: Why do the discs surrounding certain objects, such as the nuclei of active galaxies, emit jets along their polar axes? These jets are invoked by astronomers to do everything from getting rid of angular momentum in a forming star to reionizing the universe (in active galactic nuclei), but their origin is still not well understood.

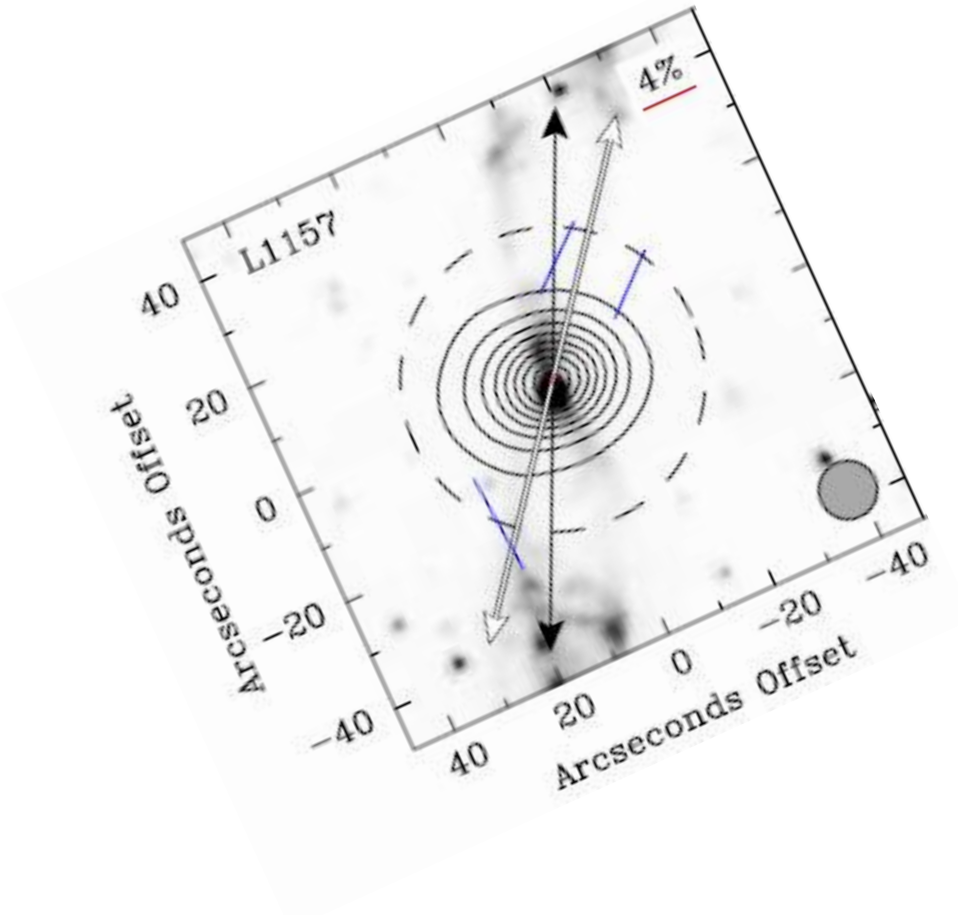
cloud

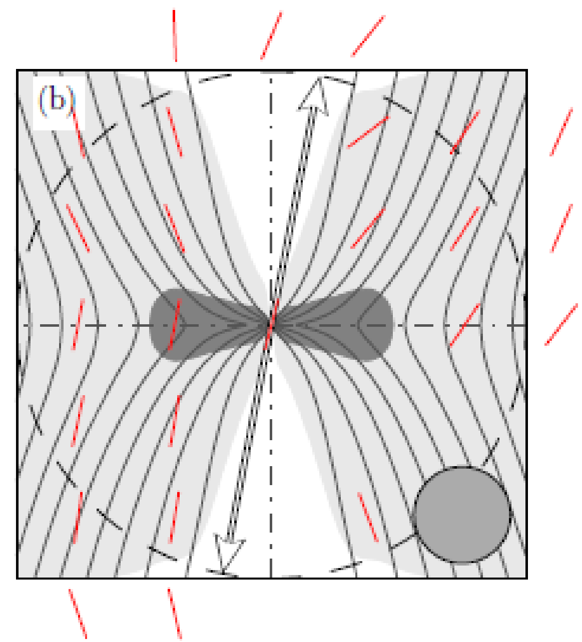


Where are astrophysical jets coming from?



A hypothesis recently transformed into evidence: aligned $B_{poloidal}$ / disk axis / bipolar jets

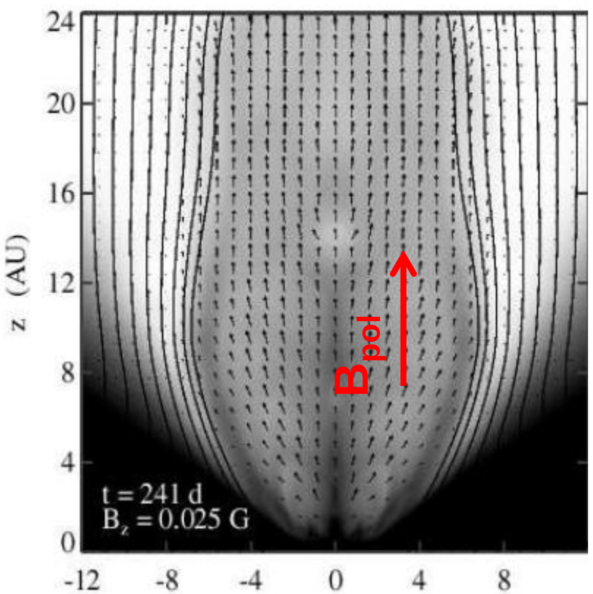




N. Chapman et al., ApJ, 770:151, 2013

Our focus: what is the effect of B_{pol}? Can it help shape the jet-like structure?

Effectiveness of B_{pol} first suggested by Matt et al. (2002)



$$F_{\perp} = \underbrace{-\frac{B_{\theta}}{\mu_0 r}\nabla_{\perp}(rB_{\theta})} + \underbrace{j_{\theta}B_{pol}}$$

This component has been studied by simulations and experiment, in our case =0

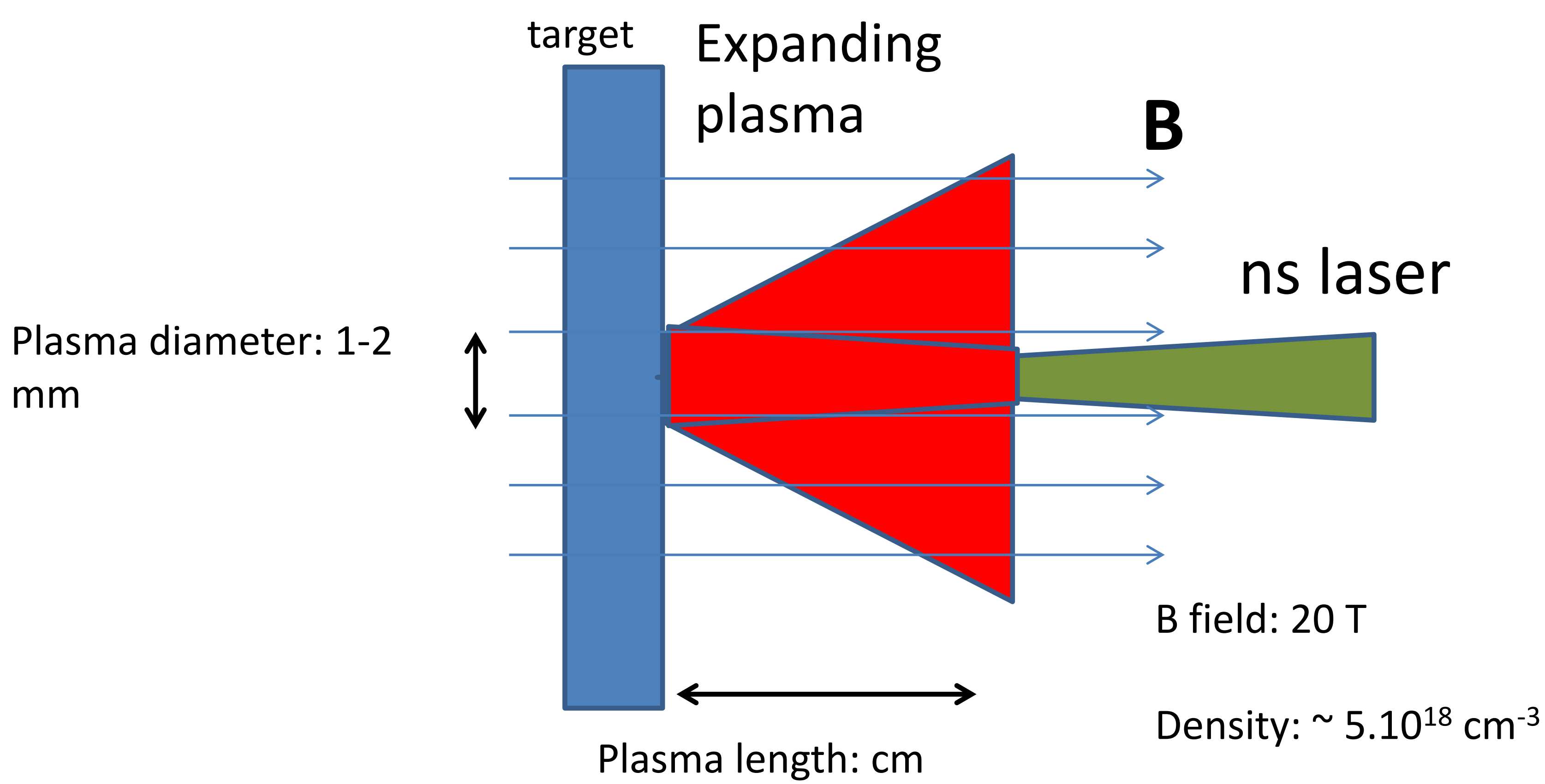
There is no experimental study on the collimation and morphology of jets

Effect we want to study

[S. Matt et al., Mont. Not. R. Astron. Soc. 000, 1-8 (2002)]

Experimentally, we want to study the influence of B_{pol} with $B_{\theta} = 0$

Q: what is really the effect of B_{pol}? → experiment



Scaling: the expanding plasma to mimic the outflow from a « Young Stellar Object »

Scaling laws [Ryutov et al., ApJ 518, 821 (1999)]

Quantity	CH	YSO
	$I=10^{12}$ W/cm^2	
Peclet	**3.5**	**1.0e11**
Reynolds	**3.7e4**	**1.0e13**
Magnetic Reynolds	**~ 50**	**1.0e15**
Mach (v_{jet} /c_s)	**1.12**	**10-50**
$\beta = p_{plasma}/p_{magnetic}$	**>>1 near source <<1 away**	**Same, <<1 from ~10s AU**

We want an ideal MHD plasma:

P_e > 1: close to 1, thermal conduction plays a minor role

R_e>>1: viscosity negligeable

R_{em}>1: magnetic field lines frozen in the outflow

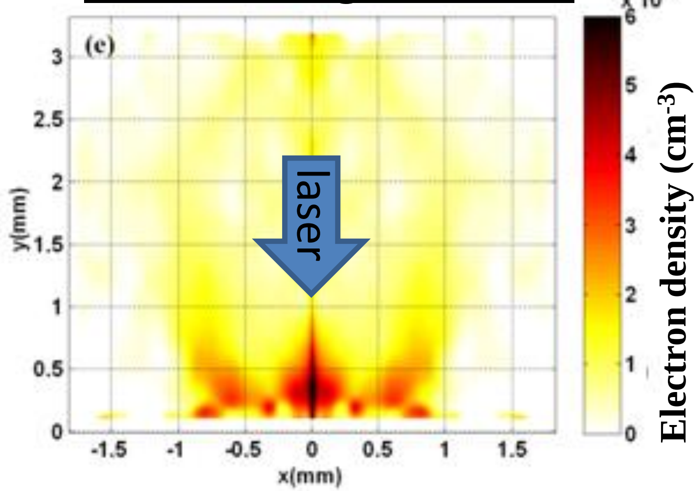
M>1: outflow supersonic

β: plasma varies from kinetic to magnetically dominated

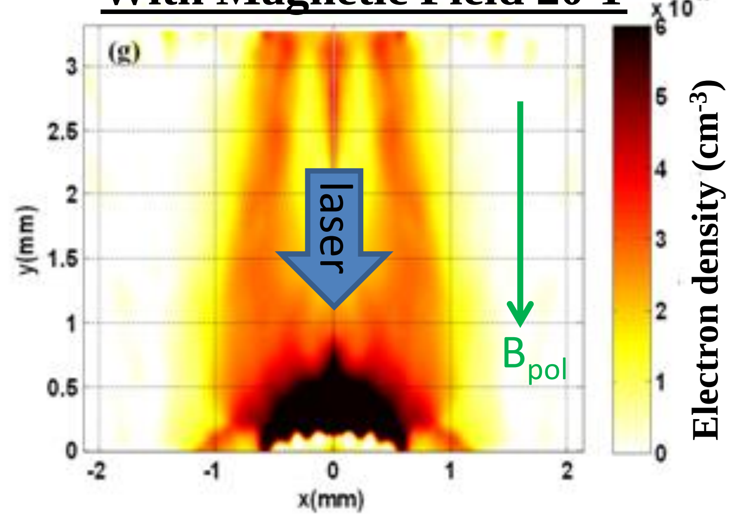
Time scales: 20 ns → 6 years

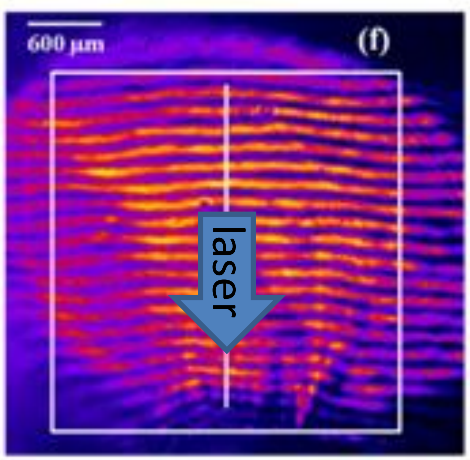
Results: strong influence of 20 T B_{pol}-field on expansion of plasmas at 10 ns

Without Magnetic Field

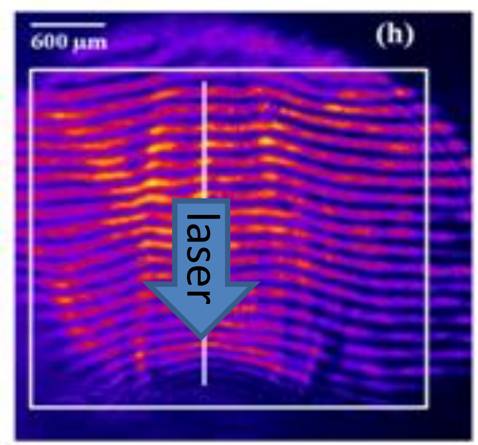


With Magnetic Field 20 T





- Time: 10 ns
- Laser intensity: ~10^{12} W.cm^{-2}

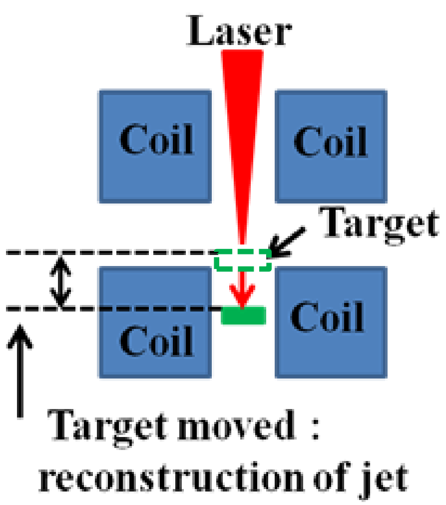


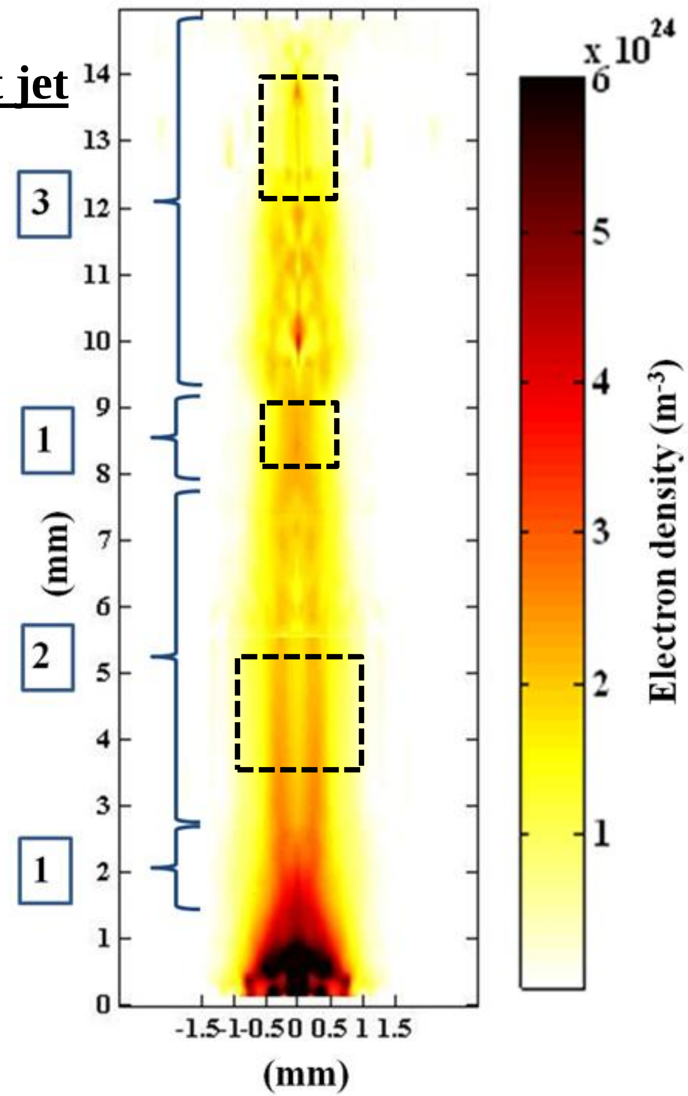
Expands almost hemispherically

Well collimated and structured

Typical experimental full jet morphology at 20 ns

Technique to reconstruct jet





1 **Standing conical shock**

2 **Formation of cavity**

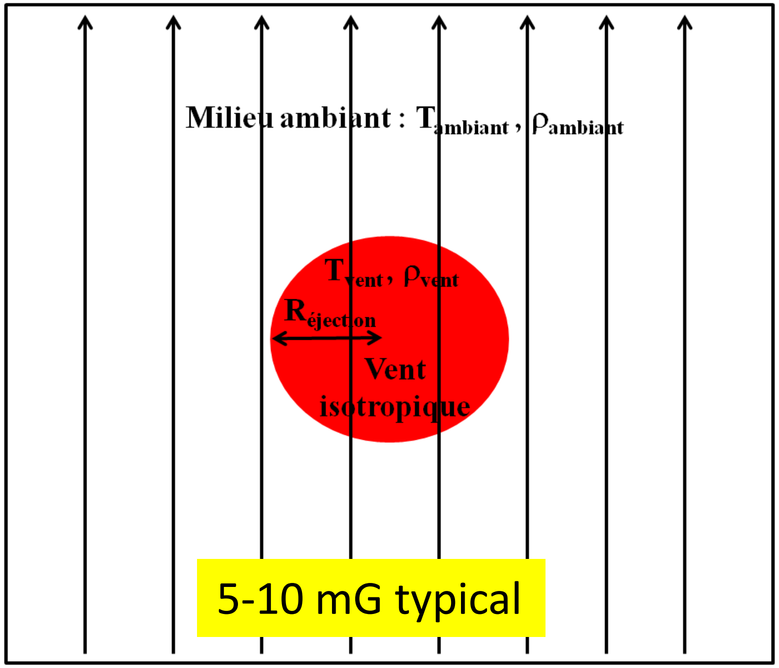
3 **Propagation of jet**

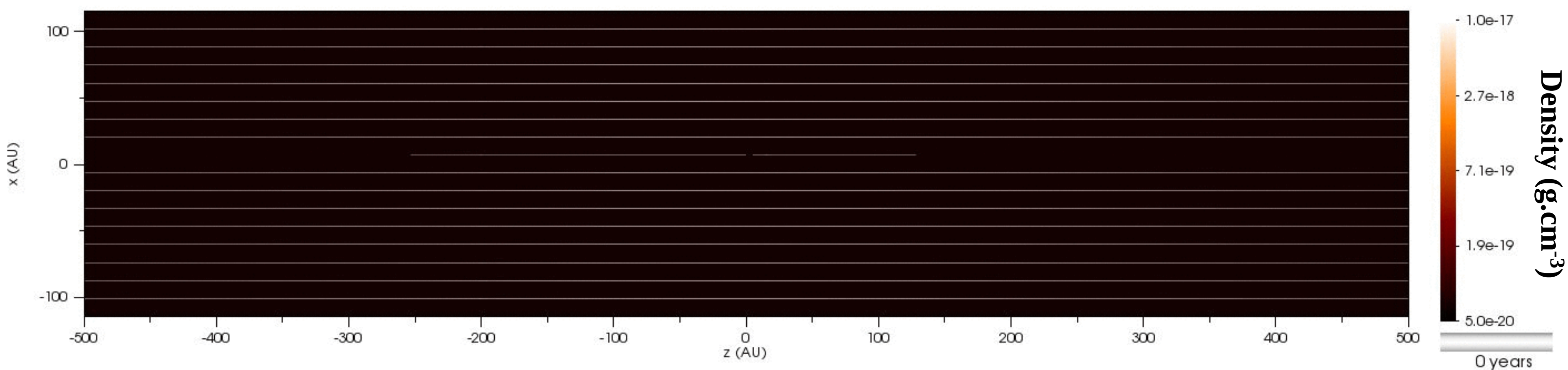
Processus of recollimation can be repeated more than once

The same morphology is found in a full-scale astrophysical simulation

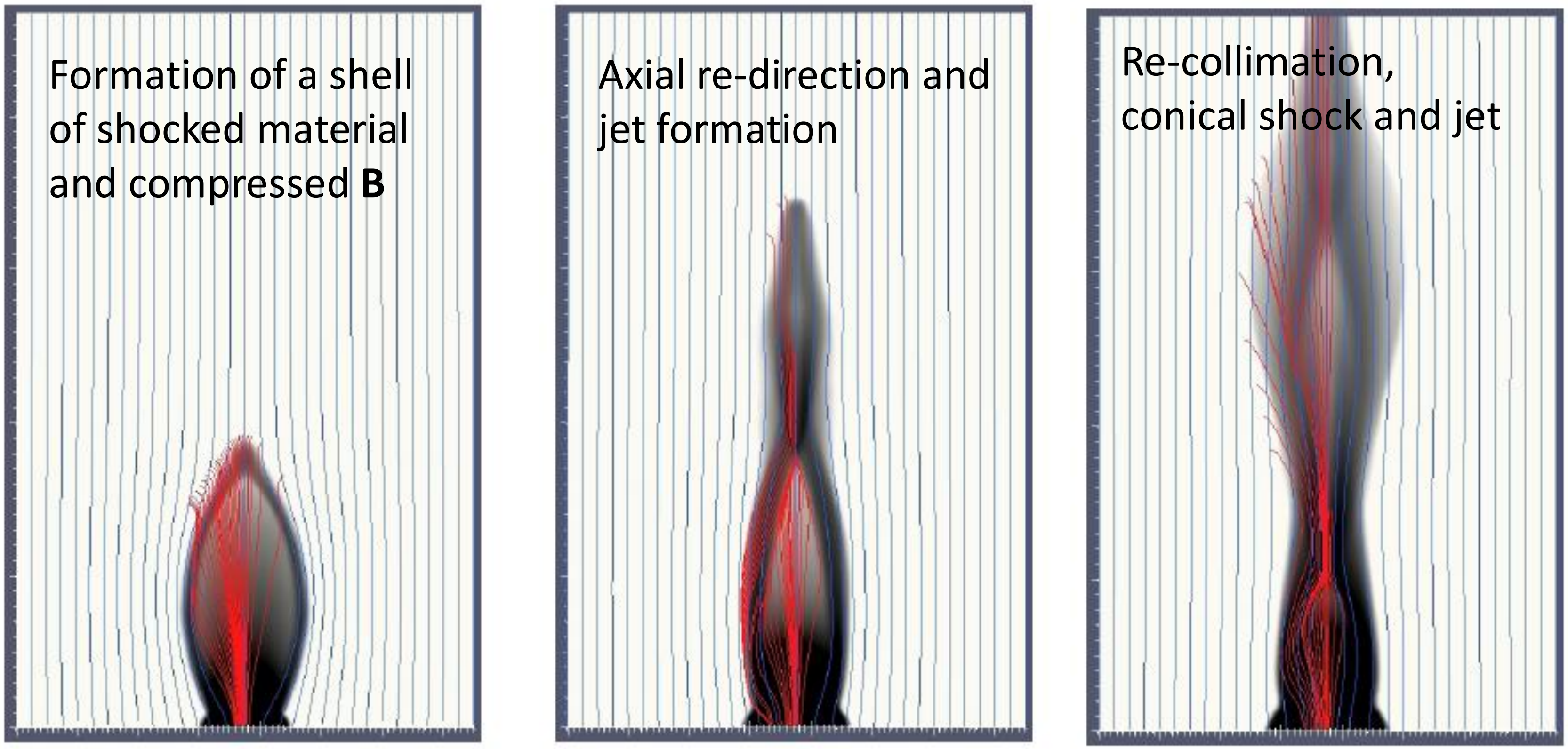
<u>Simulations performed by A. Ciardi (code RAMSES)</u>

Objet	cas 1	cas 2	cas 3
Champ magnétique (mG)	5	20	10
Taux de masse éjecté ($M_{solaire}$/an)	10^{-8}	5.10^{-7}	10^{-7}
$T_{ambiant}$ (K)	100	500	100
T_{vent} (K)	10000	500	10000
ρ_{vent} ($part.cm^{-3}$)	10^5	10^7	10^6
$\rho_{ambiant}$ ($part.cm^{-3}$)	4.10^3	4.10^5	4.10^4
$R_{éjection}$ (U.A)	8	10	10
vitesse d'éjection ($km.s^{-1}$)	200	70	130
Perturbation en vitesse (%)	5	10	5





Mechanism: shock-focusing & collimation



10 ns 20 ns 30 ns

3D MHD Gorgon code

l'Observatoire de Paris LERMA

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Parameters :
- target Al
- intensity: $1{,}5.10^{13}$ W.cm^{-2}
- B = 10 T

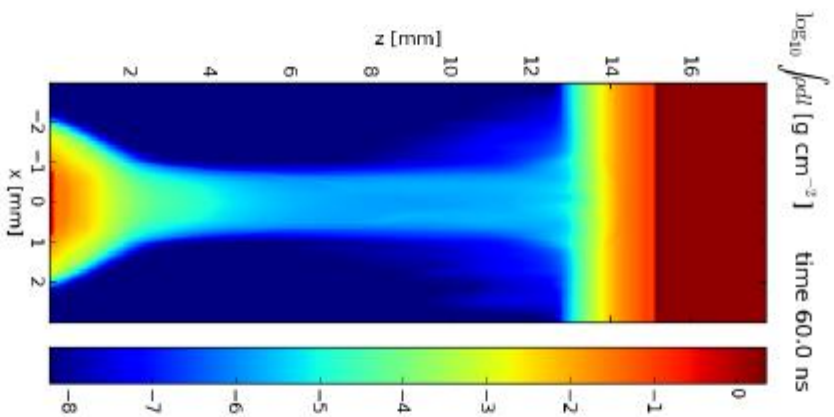
A. Ciardi et al., Phys. Rev. Lett. **110**, 025002 (2013)

Perspectives

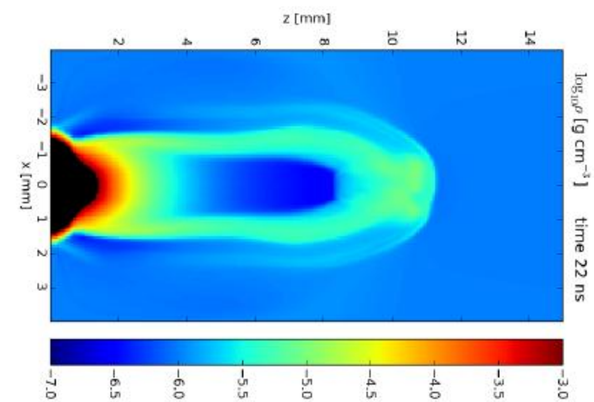
Such tight magnetized jets are a nice tool to study not only jet physics but other astrophysical phenomena

- Able to give quantitative and qualitative experimental insight on astrophysical problems
- Has potential to study e.g.

Magnetized accretion shock

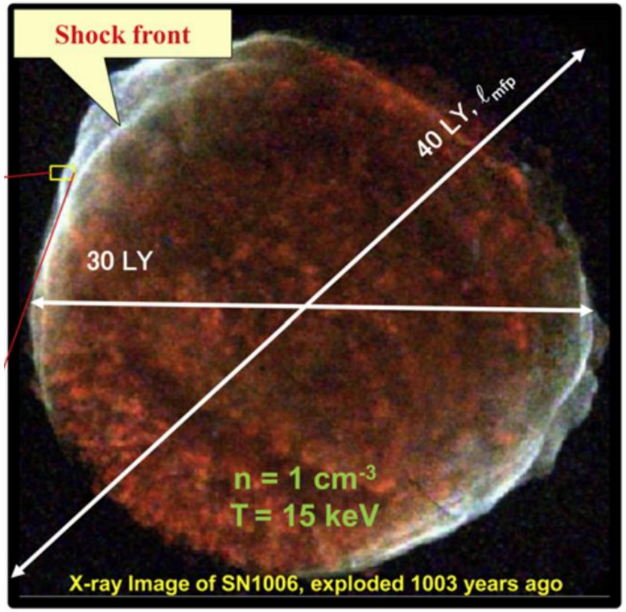


Magnetized plasma jets-ambiant medium interaction

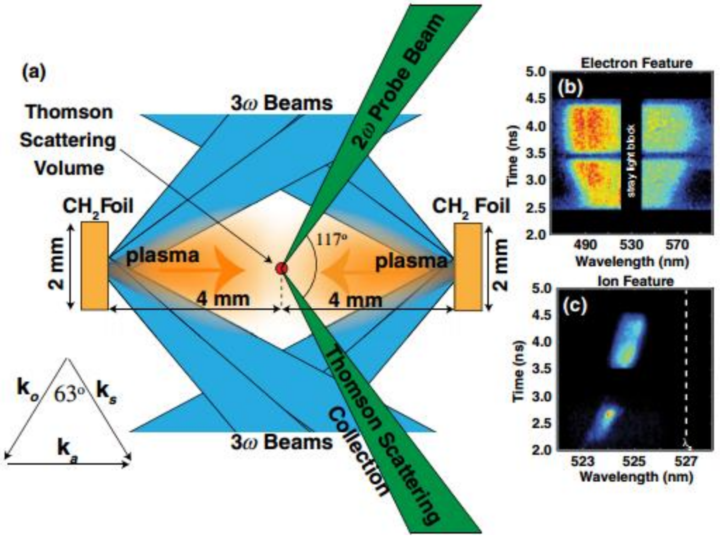


Second focus:
Magnetized Collision-less Shocks in Astrophysical Phenomena

- Energetic particle and radiation in GRB, etc are believed to be produced in shocks
- Directed energy of the ejecta is transformed in « thermal » plasma energy mostly through collisionless processes
- Electron instabilities (two-stream & Weibel) followed by i-e instabilities (filamentation), with stochastic heating of electrons in B field fluctuations



« pocket » model: counter-streaming plasmas



Gaisser, Stanev, Tilav, Front.Phys. **8** 748 (2013)
H.-S. Park, *et al.*,HEDP **8**, 38 (2012)

J.S. Ross, et al., PRL 110, 145005 (2013)
N. Kugland, et al., Nature Physics **8**, 809 (2012)

Our focus

① Experiments on Omega have flow velocities of 2000 km/s (0.007c, 20 keV).

Particle velocity seeds shock, higher velocity = more energy.

What about short-pulse lasers? → Issue with the short duration!

② The shocks are embedded in magnetic fields of various intensities

Benefit of magnetization = allows to effectively increase the growth the instabilities

BUT… an external magnetic field is not necessarily the astrophysical situation

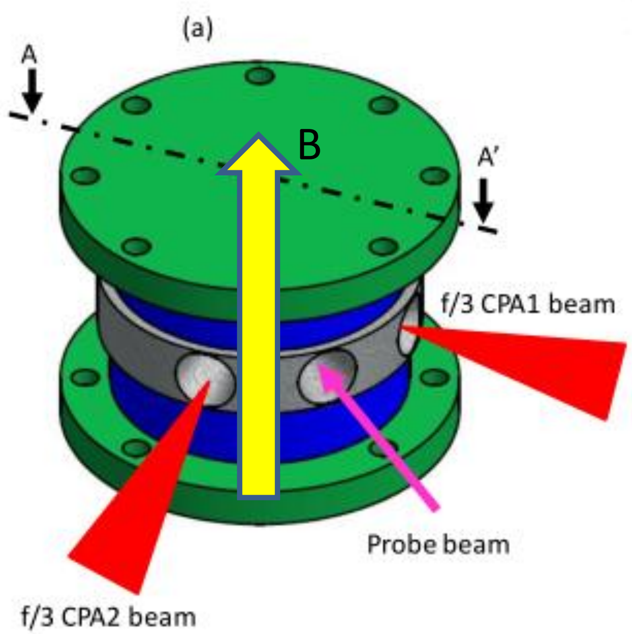
→ Focus on use of short-pulse laser driven flows AND strong magnetization to BOTH studying its intrinsic effect *and* allow growth of the instabilities

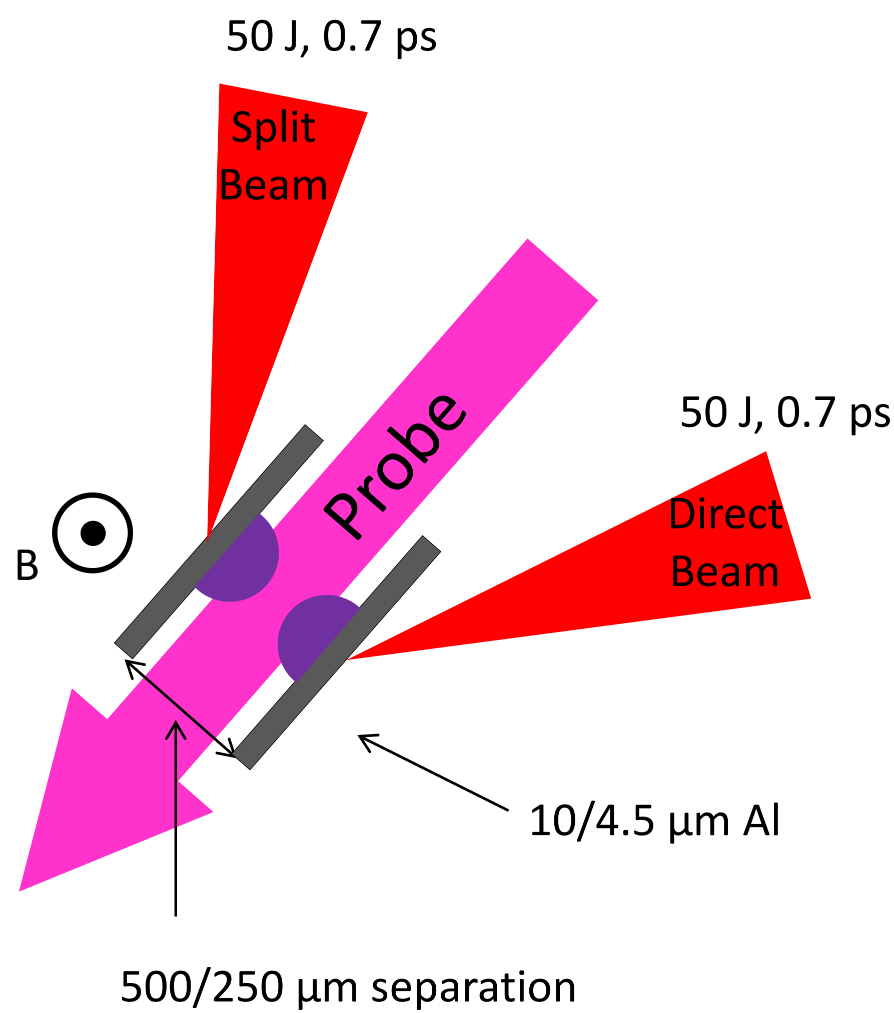
S.P. Davis *et al.,* HEDP **9**, 231 (2013).

The Titan Laser in Split Configuration Provides Double TNSA High-Velocity Flows

Protons energies : 5 - 40 MeV (β = 0.1 - 0.3)

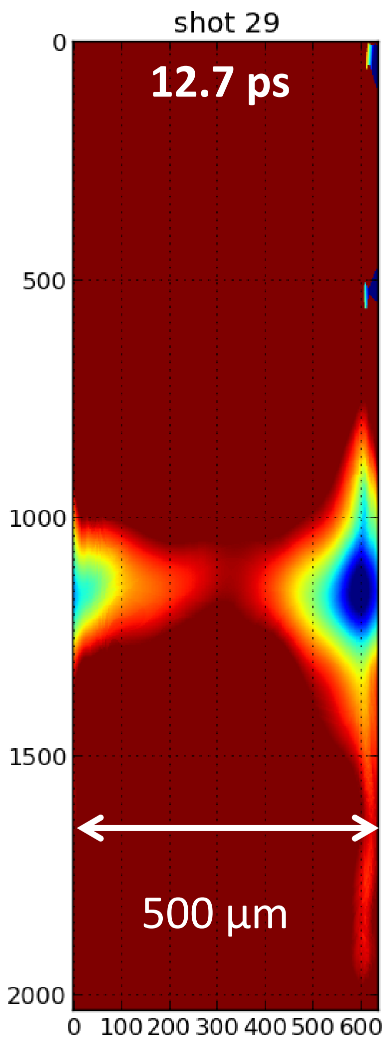
Protons: 10^{12} /shot, peak of 10 kA





Initial Plasma Falloff is Exponential from Both Sides

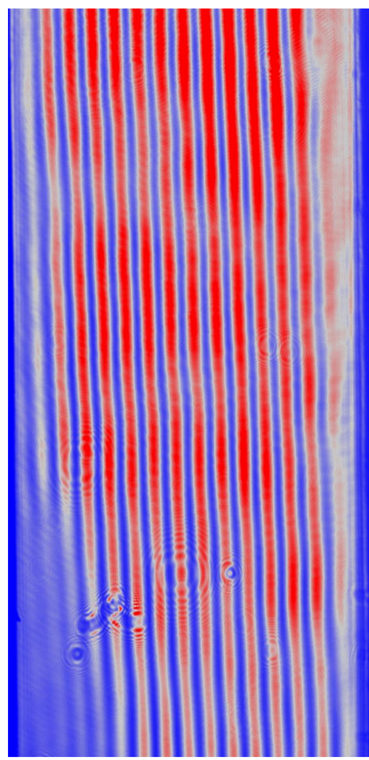
Fringe Shift

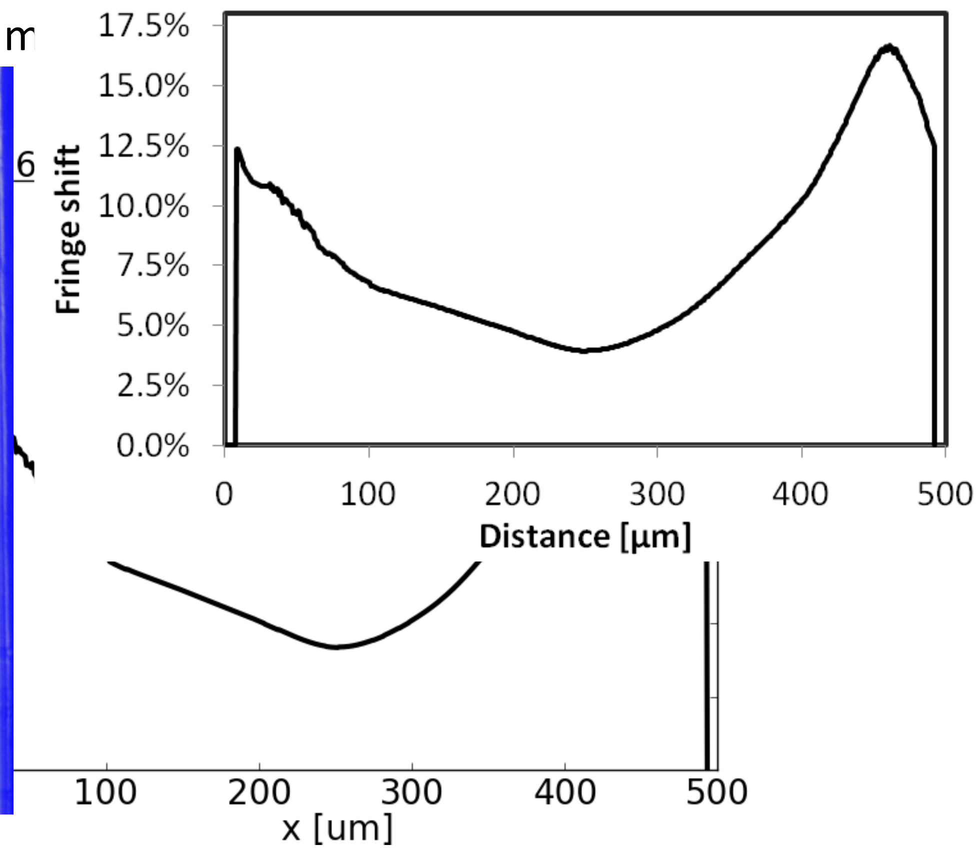


Low density plasma required good quality fringes. For instance here we have a fringe shift of 10%. Observation of shifts as low as 2% was required to see data.

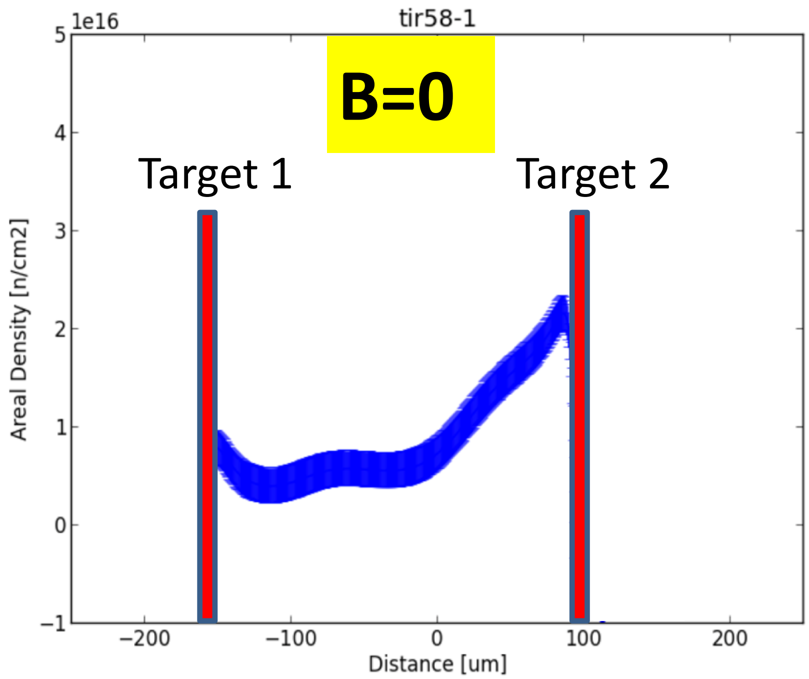
Strong density decay from the expanding TNSA beam.

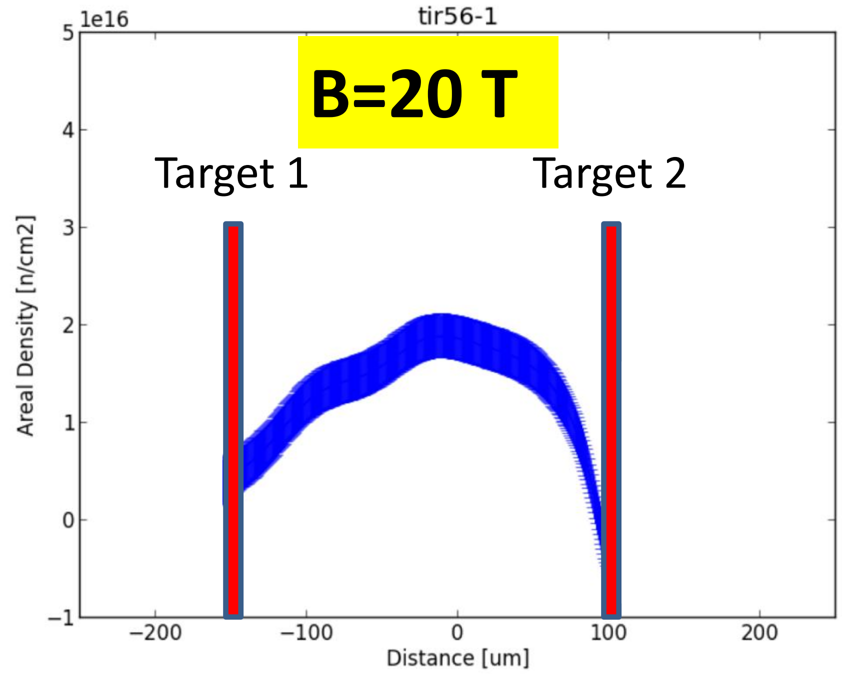
Comparing to the simple empirical estimate of density, we are within the order of m





Experimentally, we observe that the TNSA flows collision is strongly affected by the external magnetic field

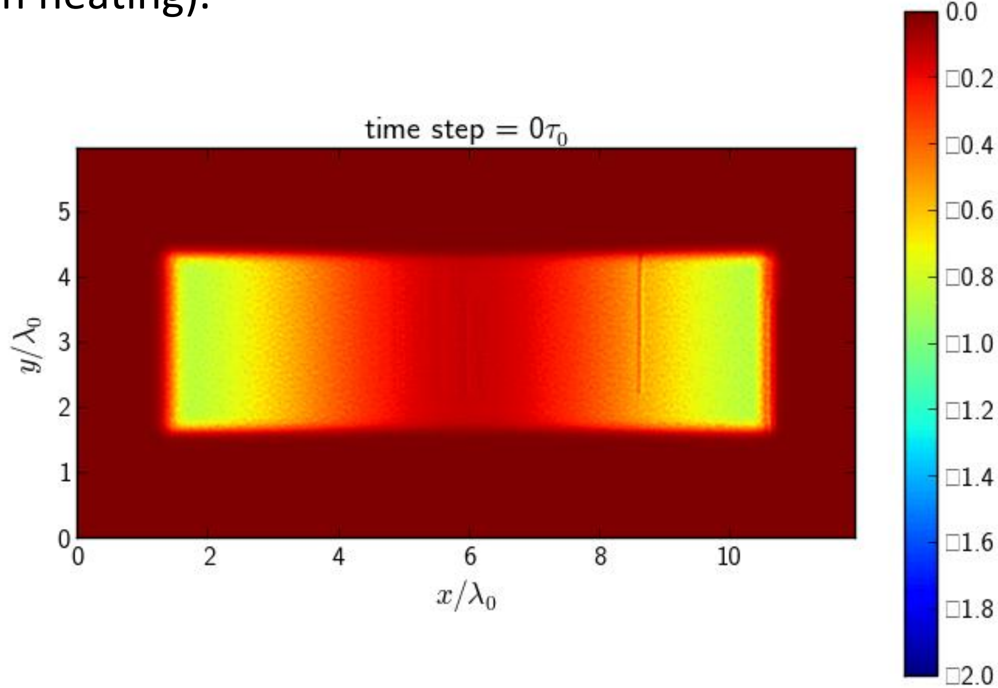




Δt=15ps, thickness=4.5 µm and separation=250 µm

Perspectives

- Finalize data analysis + ongoing simulations and theory (instabilities, reflection, role of B field, electron heating).



- Perspectives (larger 2D simulations with a realistic initial TNSA velocity profile, study of target magnetization during laser interaction, 3D simulations, other experimental diagnostics: temperature+magnetic fields+particle diagnostics, **electron-positron shocks** using high energy laser systems)

Conclusion

❖Regarding jets, we have shown that poloidal magnetic fields were very effective in producing stable collimation through a shock-focused structure, even with 40° angular offset

❖Natural explanation for « puzzling » x-ray features observed around YSO

❖Regarding collisionless shocks formation from high-velocity magnetized flows, preliminary experimental evidence seems to show the growth of some structure at the plasma crossing point →in conditions related to SNR astrophysical values of β, there is possible strong magnetic field - plasmas interaction.

❖Interaction between plasmas and magnetic fields on electron time scale may be of the great importance in astrophysics phenomena.

My perspective on JLF-Titan

- Very productive, flexible facility
- Lots of support from competent staff
- Issue with retiring/leaving staff?
- « Wish list »
    - Avoid previous users dismantling basic equipment?
    - More energetic probe (with retired equipment from Callisto?)

      → up to a few/10 J?
    - Splitting of East (ns) beam? On-shot charaterization of the East beam